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OXYGEN DECOMPRESSION TECHNIQUES FOR COMPRESSED AIR DIVING USING THE XDC-2 DECOMPRESSION COMPUTER PROGRAMMED WITH THE KIDD-STUBBS 1971 MODEL

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ABSTRACT

Decompression for compressed air diving at DCIEM has been controlled for many years by the Kidd-Stubbs (KS) 1971 decompression computer model. The current version of the KS computer is the XDC-2 digital decompression monitor. Previous experimental studies with the XDC-2, using the Doppler ultrasonic bubble detector to judge the severity of the dive profiles, have shown that the model is conservative for short bottom-time dives. However, it becomes increasingly less conservative and the decompression stress becomes increasingly more severe as the bottom times are increased. In an attempt to reduce the decompression stress and the lengthy decompression times associated with dives in the "severe stress" region, oxygen decompression procedures using the XDC-2 computer were investigated. Two procedures, based on the KS-1971 model, were established. In the first, "in-water O_2" decompression, O_2 was used at 9 metres of seawater (msw) until the decompression requirements were met. In the second, "in-water O_2 + surface decompression with O_2", normal in-water decompression was carried out to 9 msw, with the breathing gas being switched to O_2 until the end of the 9 msw stop; the diver was then returned to the surface directly and recompressed to 12 msw on O_2 in a recompression chamber. Five dive profiles - 27 msw/60 min, 30 msw/60 min, 36 msw/50 min, 45 msw/40 min, and 54 msw/30 min - were tested for each procedure. All dive subjects were monitored with the Doppler ultrasonic bubble detector. Twenty-eight man-dives were performed with "in-water O_2 ". Two incidents of decompression sickness (DCS), one mild Type 2 DCS at 45 msw/40 min and one mild Type 1 DCS at 36 msw/50 min, were observed. Thirty-six man-dives were performed with surface decompression resulting in one mild Type I DCS at 45 msw/40 min. The general conclusion of this study was that O_2 decompression procedures with the XDC-2 computers were viable procedures for reducing the in-water decompression times compared to "straight air" decompressions. In addition, the O_2 methods appeared to reduce the decompression stress considerably compared to "straight air" dives, although there was some indication that slightly more decompression was required.

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INTRODUCTION

Decompression for compressed air diving at DCIEM has been controlled in "real-time" by decompression computers for many years. The computer model was originally developed by Kidd and Stubbs using various pneumatic-mechanical analogue devices [1]. Over the years, the computers have evolved, with changes in technology, from pneumatic-mechanical to pneumatic-electronic analogue computers, and finally to microprocessor-controlled digital decompression computers. The current computer, the XDC-2, is programmed with the empirically-derived Kidd-Stubbs (1971) model (KS-1971) [2] and all calculations are done numerically based on the diver's actual depth.

In 1979 and 1980, a critical evaluation of the KS-1971 model was conducted with the XDC-2. The Doppler ultrasonic bubble detector was used to monitor venous gas emboli (bubbles) in the dive subjects to assess the "relative severity" of various dive profiles, the efficiency of the model and its operational limits [3-5]. Based on this evaluation, dive profiles (as indicated by the Doppler bubble scores) were grouped into regions of "mild to moderate", "moderate to severe", and "severe" decompression stress for "average" divers. These regions of equal stress were defined by "Isostress Curves" 1, 2 and 3, respectively [6].

The general conclusions drawn from these experiments were that the KS-1971 model was very conservative (i.e., long decompression times) for shallow and short deep dives, and that it became increasingly less conservative as the bottom times increased. Printed tables based on KS-1971 [7] were therefore limited by isostress curve 3 which defined the region of "severe" decompression stress. At extended bottom times, however, the model again became very conservative in comparison with other published tables. Figures 1 and 2 show a comparison of the KS total decompression times with those of the US Navy Standard Air Tables [8] and the Royal Navy Table 11 Air Tables [9] for 27 and 45 metres of seawater (msw).

In an attempt to reduce the decompression stress and the lengthy decompression times for dives in the region of isostress curve 3, oxygen decompression techniques with the XDC-2 were investigated. During the development of the XDC-2 decompression computer, provisions were made for O_2 decompression calculations and an "Air/O_2" switch was installed. However, such calculations had never been validated for the KS model. Therefore, a theoretical analysis was conducted to investigate the applicability of the XDC-2 to O_2 decompression, particularly for surface decompression with O_2. Appendix A provides a summary of the theoretical calculations for surface decompression.

In principle, a decompression computer model, such as the XDC-2, cannot be used for surface decompression because of the gross "violation" of the safe ascent depth (SAD) during the surface interval (SI) which invalidates the subsequent SAD calculations. Adding some

measure of additional decompression time can, however, compensate for the period spent in violation of the model. One method of such compensation is to give additional decompression in the recompression chamber (RCC) after the SAD reaches "0". This can be accomplished, for example, by a very slow rate of ascent from the RCC stop to the surface.

Once the feasibility of using the XDC-2 for O_2 decompression had been established, two specific O_2 decompression procedures were developed and tested in the DCIEM Dive Research Facility (DRF). These were the "in-water O_2 decompression" procedure and the "in-water O_2 + surface decompression with O_2" procedure. This report describes these tests which resulted in a significant reduction of the in-water decompression times and the decompression stress experienced in the region of isostress curve 3.

EXPERIMENTAL METHODS

1. Oxygen Decompression Procedures with the XDC-2

The ascent procedures established for the two O_2 decompression methods, using the XDC-2 decompression computer, were as follows.

a. "In-Water O_2" Decompression

(1) The diver does a normal XDC-2 ascent at 18 msw/min or slower to 9 msw and stops.

(2) The diver's gas and the XDC-2 are switched to O_2. The diver remains at 9 msw until the XDC-2 SAD reads "0".

(3) The diver then surfaces at 9 msw/min.

b. "In-Water O_2 + Surface O_2" Decompression

(1) The diver does a normal XDC-2 ascent at 18 msw/min or slower to 9 msw and stops.

(2) The diver's gas and the XDC-2 are switched to O_2. The diver remains at 9 msw until the XDC-2 SAD reads "6 msw". (Note 1)

(3) The diver is then brought directly to the surface on O_2, undressed and then recompressed to 12 msw on O_2 in the RCC as rapidly as possible. (The time from leaving the 9 msw in-water stop to reaching the 12 msw RCC stop must not exceed 7 min.) (Note 2)

(4) The diver remains at 12 msw breathing O_2 until the XDC-2 SAD is "0".

(5) The diver then surfaces at 1 msw/min on O_2. (Note 3)

All dives were conducted in the DRF which is equipped with a horizontal (isobaric) wet chamber. Water temperature was not controlled and ranged from 11.2°C to 20.0°C.

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Note 1. Under normal operation of the XDC-2, SAD = 6 msw indicates the completion of the 9 msw stop and the beginning of the ascent to the 6 msw stop.

2. The 7 min SI was chosen since the DRF requires nearly 2 min to surface from 9 msw because of vent rate limitations. In addition, a 7 min SI also reduces the chances for "omitted decompression" in operational scenarios.

3. The slow ascent rate from 12 msw in the RCC is to partially compensate for the violation of the model during the SI.

Four standard profiles were chosen for the investigation of the two O_2 decompression methods.

a) 27 msw/60 min - on isostress curves 2
b) 36 msw/50 min - beyond isostress curve 3
c) 45 msw/40 min - beyond isostress curve 3
d) 54 msw/30 min - beyond isostress curve 3

A fifth profile, 30 msw for 60 min (on isostress curve 3) was added since it was required for another separate experiment. Table 1 shows the decompression stops for the five profiles tested. (Calculations have been made for an altitude of 200 metres, the altitude of the DCIEM site.) The in-water stop times shown include the travel time to those stops. Figure 3 shows a comparison of the two O_2 decompression profiles for a dive to 45 msw for 40 min. Also shown is the same dive done on compressed air only.

For the actual dives, decompression was carried out in the traditional method using tables (Table 1) although three XDC-2's and one digital data logger were on-line at all times. This approach was taken to further verify the correct function, reliability, and precision of the XDC-2's for O_2 decompression and to eliminate the possibility of having to abort an experiment as a result of computer failure. For example, if a computer ever indicated a deeper SAD than that required by the tables, control was to be shifted to the "deepest" computer for the remaining decompression. This situation never occurred during these experiments.

Descent to depth was at 18 msw/min. Ascent was at 18 msw/min to the first stop and between stops. During the actual dives, travel time to stops was counted as "stop time" except at the 9 msw O_2 stop where the time was not started until all subjects were confirmed to be breathing O_2. The full 7 min SI was used for all surface decompression dives. Ascent from the 9 msw O_2 stop was done in 2 min and descent back to 12 msw in the RCC was done in 1 min.

2. Dive Subjects

Each dive included a minimum of a "wet-working" diver, a "dry-resting" diver, and a standby diver. The " wet-working diver" wore a Viking dry suit/Woolly Bear underwear combination with a Superlite 17B helmet. The standby diver wore a wet suit/Hookah gear combination. The "dry-resting" diver wore RCC coveralls. Wet divers worked on a bicycle ergometer at 65% of maximal heart rate at surface in a 10 min work/5 min rest cycle for 40, 50, and 60 min bottom times and at 80% of the maximal heart rate in a 6 min work/4 min rest cycle for the 30 min bottom time.

Both the wet-working diver and the dry-resting diver were qualified Canadian Forces Clearance Divers. The standby divers were selected from the DCIEM roster of qualified Ships Divers and Ships Diving Officers. All subjects had a minimum of 48 hours between dives and were not to engage in strenuous physical exercise for 24 hours

pre-dive and 12 hours post-dive. (For the dives to 30 msw, the subjects had 7 days between the dives.) Table 2 shows the physical characteristics of the dive subjects who participated in these dives. The percentage body fat, using the equation of Durnin and Womersly [10], was estimated by summing skinfolds measured at three sites - the triceps, subscapula, and suprailiac.

3. Doppler Ultrasonic Monitoring Procedures

The instrument used for monitoring bubbles was the model "DUG" Bubble Detector developed by the Institut National des Sciences Appliquées de Lyon for the Centre d'Etudes et de Recherches Techniques Sous-Marines in Toulon, France, and manufactured by Sodelec SA of Marseille, France.

All divers were monitored for bubbles at the precordial site (right ventricle and/or pulmonary artery) and the subclavian sites (both left and right shoulders). Two conditions were used at each site; in the first condition, the diver stood at rest, and in the second, the diver performed a specified movement. For the precordial site, this movement was a deep knee-bend - squatting and returning to the standing position in a continuous, smooth motion. For the subclavian sites, the movement consisted simply of clenching the fist on the side being monitored.

The Doppler ultrasonic signals, which include contributions from blood flow, cardiac motion, and bubbles, were simultaneously recorded on audio magnetic tape and assessed aurally. In cases of doubt, the tape recording was replayed and compared with the pre-dive reference recording. The bubble signals were classified according to the Kisman-Masurel code [11], which uses three criteria (on a scale from 0 to 4):

a) the number of bubbles per cardiac signal,
b) the percentage of cardiac cycles with bubbles, and
c) the amplitude of the bubble signals relative to the background.

The resulting 3-digit code was used to obtain a global bubble grade from 0 to 4. (The bubble grade scale is similar to the other commonly used bubble grade scale developed by Spencer [12].)

Monitoring was performed by a team of experienced technicians. A reference signal was recorded before each dive, and each subject was monitored at half-hour intervals for at least two hours following the end of decompression. During this time, the divers were asked to rest in the immediate vicinity, and to refrain from excessive post-dive activity, since this is thought to contribute to decompression problems [3]. If bubbles were detected, the subject was required to remain under observation until the bubbles diminished to insignificant numbers. The subjects were asked to report any pain or other symptoms of decompression sickness (DCS). The attending Diving Medical Officer considered subjective symptoms only, not bubble grades, in deciding whether to treat for DCS.

RESULTS

1. Dive Profiles

Table 3 shows the actual dives carried out, number of subjects in each dive, the number of wet divers, and the water temperature. An examination of the actual dive profiles as recorded on the digital data logger showed that the total decompression times were generally 1-3 min longer than those prescribed in Table 1, particularly at the beginning of the series. This was primarily caused by delays at the 9 msw stop before all subjects were confirmed as being "on O_2 ". The digital data logger showed that the XDC-2's performed as predicted. The XDC-2 SAD's were, at all times, slightly shallower than the table stops. It was also noted that the XDC-2 SAD generally indicated approximately "-1" msw after the slow ascent from the 12 msw RCC stop.

2. Doppler Results

Table 4 presents the peak bubble grades for the precordial and subclavian sites, for the rest and movement conditions, for each man-dive. In addition, Table 4 gives the time, T, from the start of decompression (i.e., "leaving bottom"), when the maximum bubble grades were observed. The results are grouped by subject, to highlight the differences between decompression methods, instead of the differences between divers. Bubbles were observed more frequently in the subclavian veins (45.3% of 64 man-dives) than in the precordial region (18.8%). Overall, 51.6% of the man-dives resulted in observable bubbles in either precordial region or in the subclavian veins.

Table 5 presents the same information as Table 4 but grouped by decompression method and profile. This allows a much easier comparison of the dive profiles. For example, it can be seen that the dive to 54 msw for 30 min with in-water O_2 decompression appeared to be the most stressful dive with 6 of the 7 subjects having observable bubbles in the precordial region and/or the subclavian sites. The same dive with surface decompression on O_2 also resulted in 5 out 6 subjects having observable bubbles.

Tables 6 and 7 show a summary of the information presented in Table 5. Table 6 gives the number of occurrences of peak bubble grades for the precordial site, for both rest and after movement, and Table 7 gives the corresponding numbers for both subclavian veins. The number of incidents of DCS for each profile is also given.

3. Decompression Sickness

There were three cases of DCS. Two incidents were associated with in-water O_2 decompression. Subject SGG experienced mild Type II DCS (numbness in his left hand, pain from the left elbow to the shoulder) after a dive to 45 msw for 40 min as the wet, working diver. No bubbles were detected in the precordial region and only a few

bubbles were detected in his left shoulder at 131 min following the start of decompression. Treatment commenced at 195 min.

Dry-resting subject DN had mild Type I DCS following a dive to 36 msw for 50 min. In this case, also, no bubbles were detected in the precordial region. However, grade 2 bubbles were observed in the right shoulder from 70 min to 154 min following decompression.

One incident occurred with surface decompression. Wet-working diver SMD had mild Type I DCS (pain in the left knee) at 270 min following the start of decompression after a dive to 45 msw for 40 min. No bubbles were observed in the precordial region at rest, but grade 3+ bubbles were observed after movement from 92 to 197 min following the start of decompression. A few bubbles were also detected in the shoulders and in the inferior vena cava.

DISCUSSION

1. Comparison of Profiles with Standard Air Dives

All the dives tested were near the KS isostress curve 3 for standard air dives (region of severe decompression stress). During the XDC-2 validation dives [3,4], a number of standard air dives at or near isostress curve 3 were tested. These standard air dives were:

a) 30 msw for 55 min,
b) 36 msw for 50 min,
c) 45 msw for 30 min, and
d) 54 msw for 25 min.

For these dives, decompression was carried out continuously, with the actual depth being kept equal to the SAD, instead of in the traditional table format. All these dives were found to produce severe decompression stress as indicated by the Doppler bubble detector. The results of the decompression methods using O_2 can be compared with these standard air dives to determine the effectiveness of O_2 in reducing the decompression stress.

The comparison showed that the dives using O_2 during decompression resulted in fewer bubbles and that bubbles tended to appear later. The percentage of man-dives with observable bubbles in the precordial region following movement were as follows.

	"Air"	"In-Water"	"Sur D"
No bubbles	15.7%	78.5%	83.3%
Grade 1 bubbles	7.8%	3.6%	8.3%
Grade 2 bubbles	15.7%	0.0%	2.8%
Grade 3 bubbles	47.1%	14.3%	5.6%
Grade 4 bubbles	13.7%	3.6%	0.0%
No. of man-dives	51	28	36

For the standard air dives, there were five definite and two probable cases of DCS (13.7%). For in-water O_2 decompression, there were only two incidents (7.1%) and for surface decompression, there was only one incident (2.8%).

A comparison of individual profiles showed that there were some dramatic differences. For example, the standard air dive to 36 msw for 50 min resulted in 50% of the subject (out of 6 subjects) having grade 3 bubbles in the precordial region after movement and the other 50% having grade 4 bubbles. Three of the subjects had to be treated for DCS. The same profile with O_2 during decompression did not appear to be too stressful, although one incident of DCS resulted from the in-water O_2 procedure.

Table 8 gives the equivalent standard air decompression times generated by the KS model for 200 metres altitude. A comparison of

these decompression times with those in Table 1 showed that for the in-water O_2 procedure, the decompression time was reduced to about two-thirds of that for standard air. Hence, the in-water O_2 method will be effective since it not only reduces the in-water exposure but it also decreases the decompression stress. The most effective method for reducing the in-water decompression time is the surface decompression method. A comparison of the decompression times with the standard air times shows that the in-water exposure time during decompression is reduced to approximately 15% for the shallower dives and to about 25% for the deeper dives.

2. Comparison of the Two O_2 Decompression Procedures

A comparison between the two O_2 methods shows that the surface decompression procedure appeared to be slightly more effective than the in-water O_2 procedure. For all the surface decompression dives (36 man-dives), 44.4% of the man-dives resulted in some bubbles being observed in the precordial region and/or shoulders, whereas for the in-water O_2 dives (28 man-dives), 60.7% of the man-dives resulted in some bubbles being observed.

The surface decompression procedure tested here differed from normally accepted practice in several ways. First, the ascent rate to the first stop was at 18 msw/min; second, O_2 was used at the 9 msw in-water decompression stop; third, the surface interval allowed from leaving 9 msw until the 12 msw RCC stop was reached was 7 min rather than the conventional 5 min; and finally, no air breaks were used during the O_2 stop in the RCC. In addition, the ascent to surface from the RCC stop took 12 min instead of 2 min. This slow ascent rate was used to provide additional O_2 decompression to compensate for the violation of the SAD during the surface interval. (This slow rate of ascent was also used by Arntzen and Eidsvik [13] in their modification of the US Navy "Surface Decompression Table using Oxygen" [8].)

As noted earlier, the actual decompressions were conducted by following preset decompression tables rather than by following the computed SAD on the XDC-2 computer. Since the O_2 stop time at 9 msw was not started until all subjects were confirmed to be on O_2, the total decompression times were always slightly longer than prescribed by the tables. As a result, the dive subjects always remained below the SAD, and the total decompression actually experienced by the subjects was slightly more conservative than that required by the KS model. The preset profiles were also calculated for an altitude of 200 metres. This made the decompression times about 2 min longer than those which would have been calculated for sea level dives. If the dive profiles had been derived from the KS model for sea level conditions and had been dived exactly, a more severe decompression stress likely would have resulted.

3. Decompression Sickness and Bubbles

Unlike incidents of DCS observed previously on standard air dives, the incidents of DCS using O_2 during the decompression showed

that there appeared to be little correlation between high bubble scores and DCS. In the two incidents arising from the in-water O_2 dives, no bubbles were detected in the precordial region at rest or after movement. In one case, only a few bubbles were detected in one shoulder and in the other case, grade 2 bubbles were detected for a long time in one shoulder. In the incident arising from surface decompression, bubbles were detected in the precordial region only after movement. A few bubbles were observed in the shoulders. These cases tend to confirm the viewpoint that DCS is caused by trapped bubbles which cannot be detected by the Doppler bubble detector.

The absence of detectable bubbles, however, does not mean that there are no circulating bubbles. There is a bubble size threshold before bubbles can be detected in the precordial region because of the high background noise level due to heart wall motion, valve noises, and the large scattered signal from the red blood cells. This threshold size has been estimated to be around 80 to 100 micrometres in diameter. Smaller bubbles may not be detected.

In the subclavian veins, much smaller bubbles can be detected because of the low background noise level. In theory, all bubbles detected here should eventually pass into the precordial region. However, in many cases, bubbles were detected in the subclavian veins but not in the precordial region. This may be a result of these bubbles being too small to be detectable in the precordial region or because some of these bubbles may have been resorbed.

CONCLUSIONS

The general conclusions drawn from these experiments on O_2 decompression procedures with the XDC-2 computer are:

a) The proposed O_2 decompression methods are viable procedures which reduce the "in-water" decompression times considerably in comparison with "straight air" decompression based on the same model.

b) The O_2 decompression methods appear to reduce the decompression stress compared to "straight air" decompression for similar dives. As indicated by the bubbles detected by the Doppler ultrasonic bubble detector, surface decompression with O_2 appears to be slightly more efficient than "in-water O_2". However, the overall results indicate that some divers were, in general, not yet sufficiently decompressed on some of these profiles. It is felt that an additional 5 to 7 min of total decompression time over the sea level values for these dive profiles would reduce the decompression stress to the "moderate to severe" region for most divers.

c) The onset of detectable bubbles appears generally to occur later with O_2 decompression than with air decompression.

d) The absence or relatively low count of bubbles does not preclude the occurrence of DCS. However, the presence of large numbers of bubbles appears to indicate the "inefficiency" or "incompleteness" of the decompression.

e) The XDC-2's, modified with external "Air/O_2" mode switches, performed as designed and predicted by the model. Thus, the XDC-2 can be used with confidence for reliable "real-time" air/O_2 decompression control.

f) The use of the traditional staged ascent procedure instead of continuous ascent following the SAD is much easier operationally even with a decompression computer. The easiest method is to ascend to the deepest multiple of 3 msw (or 10 feet of seawater (fsw)) deeper than the indicated SAD and remain there until the next shallower 3 msw (or 10 fsw) multiple is indicated before ascending to that stop.

g) The slow ascent rate from the RCC stop (1 msw/min) for surface decompression may be difficult to control in small diving vessels. As the XDC-2's generally indicated a SAD of "-1.0" msw on surfacing after the slow ascent, remaining at the 12 msw RCC stop until the SAD reads "-1.0" msw ("3" fsw) and then surfacing in 2 min should provide the equivalent "compensatory" decompression time. Further, this compensation for the "violation" of the SAD during the SI will then always be directly proportional to the depth/time exposure.

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TABLE 1

DECOMPRESSION PROFILES TESTED

A. In-Water Oxygen Decompression

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)					Decom. Time (min)
		Air			O_2		
		18	15	12	9	Asc	
27	60	-	-	-	22	2	24
30	60	-	-	-	30	2	32
36	50	-	-	5	33	2	40
45	40	-	5	6	38	2	51
54	30	3	5	6	37	2	53

B. Surface Decompression with Oxygen

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)									Decom. Time (min)
		In-Water Stops				Surface			Chamber		
		Air			O_2	O_2	Air	O_2	O_2		
		18	15	12	9	Asc	SI	Des	12	Asc	
27	60	-	-	-	3	2*	4	1	12	12	34
30	60	-	-	-	5	2*	4	1	18	12	42
36	50	-	-	5	5	2*	4	1	22	12	51
45	40	-	5	6	5	2*	4	1	26	12	61
54	30	3	5	6	5	2*	4	1	25	12	63

Note: Decompression times calculated for 200 metres altitude
Asc = ascent; Des = descent; SI = actual time on surface
* Ascent time set by DRF vent rate limitations (see text)

TABLE 2

SUBJECT STATISTICS

DIVER	AGE	WEIGHT (kg)	HEIGHT (m)	SUM OF SKINFOLDS (mm)	PERCENT BODY FAT	RECOMMENDED WEIGHT (kg)	NUMBER OF DIVES
LBC	37	79	1.77	37.4	19.0	78-83	2
JDJ	37	74	1.71	----	26.0	67-71	2
RSD	32	86	1.73	46.4	22.1	82-86	1
DE	30	66.5	1.74	25.1	13.4	70-74	4
SGG	28	81	1.71	50.7	23.3	76-80	9
ALH	35	86	1.80	47.4	22.4	81-86	8
JH	32	72	1.75	47.1	22.3	68-72	2
BH	32	79	1.71	32.3	17.0	80-84	2
SMD	29	66	1.69	27.2	14.6	69-73	8
BM	36	71	1.72	36.2	18.6	70-74	4
MN	37	76	1.82	30.7	16.2	77-82	5
DN	29	71	1.80	37.1	18.9	70-74	7
GP	40	70	1.72	36.2	18.6	69-73	3
AR	32	60	1.67	----	21.5	57-61	5
KR	36	73	1.80	37.1	18.9	72-76	1
RW	45	76	1.79	24.5	13.1	80-85	1
mean	34.2	74.2	1.75	36.8	19.1		
s.d.	4.6	7.1	0.05	8.5	3.7		

TABLE 3

DIVES INCLUDED IN THIS STUDY

DEPTH (msw)	BOTTOM TIME (min)	METHOD	DATE	NO. OF SUBJ.	NO. WET DIVERS	WATER TEMP. (°C)
27	60	IW	82-11-04	3	1	14
27	60	IW	82-12-08	3	1	15.6
30	60	IW	82-11-24	3	1	11.2
36	50	IW	82-11-03	3	1	13
36	50	IW	82-11-29	3	1	11.2
45	40	IW	82-11-22	3	1	12
45	40	IW	82-12-01	3	1	15
54	30	IW	82-12-02	4	1	15.5
54	30	IW	82-12-07	3	1	14
27	60	SD	82-11-01	3	1	20
27	60	SD	82-11-02	3	1	20
27	60	SD	82-11-15	3	1	12.3
27	60	SD	82-12-09	3	1	16
30	60	SD	82-11-09	3	1	15
36	50	SD	82-11-04	3	1	14
36	50	SD	82-11-15	3	1	12
36	50	SD	82-12-06	3	1	13.5
45	40	SD	82-11-08	3	1	13.5
45	40	SD	82-11-18	3	1	12.6
54	30	SD	82-11-08	3	1	13.6
54	30	SD	82-11-11	3	1	16

SD - surface decompression with oxygen
IW - in-water decompression with oxygen

TABLE 4

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES BY SUBJECT, PROFILE, AND DECOMPRESSION METHOD

DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
1. LBC	27/60	SD	S	0	-	0	-	1/1	79	
2. LBC	54/30	IW	DR	0	-	0	-	0	-	
3. JDJ	27/60	SD	S	0	-	0	-	0	-	
4. JDJ	45/40	SD	S	0	-	0	-	0	-	
5. RSD	27/60	IW	DR	0	-	0	-	0	-	
6. DE	27/60	SD	S	0	-	0	-	0	-	
7. DE	36/50	SD	S	0	-	0	-	0	-	
8. DE	45/40	IW	S	0	-	0	-	0	-	
9. DE	54/30	IW	S	3/3	170	1/1	218	2/3	195	
10. SGG	27/60	IW	DR	0	-	0/1	94	0	-	
11. SGG	27/60	IW	WW	0	-	0/2	116	0	-	
12. SGG	27/60	SD	DR	0	-	0	-	0	-	
13. SGG	36/50	SD	WW	0	-	0	-	0	-	
14. SGG	36/50	SD	DR	0	-	0	-	0	-	
15. SGG	45/40	IW	WW	0	-	0	-	1/1	131	Yes
16. SGG	45/40	IW	DR	0	-	0	-	0	-	
17. SGG	45/40	SD	DR	0	-	0	-	1+/2	142	
18. SGG	45/40	SD	WW	0	-	0	-	0	-	
19. ALH	27/60	SD	DR	0/2	67	0/1	45	3/4	104	
20. ALH	27/60	SD	WW	0/1	91	0	-	1/1	116	
21. ALH	30/60	IW	DR	0	-	0	-	2/2	86	
22. ALH	30/60	SD	WW	0	-	0	-	1/1	55	
23. ALH	36/50	IW	DR	0/1	60	0	-	0	-	
24. ALH	36/50	IW	WW	0	-	3/3+	99	1/1	224	
25. ALH	54/30	IW	DR	2/3	225	1/1	277	2/1+	179	
26. ALH	54/30	IW	WW	3/3	117	2/1	174	3+/3+	140	

Explanation of Symbols

Method: SD - surface decompression with oxygen
IW - in-water decompression with oxygen

Role: WW - wet working diver DR - dry resting subject
S - standby diver L - team leader, dry

Code: P - precordial LS - left shoulder RS - right shoulder
a/b: a - bubble grade for rest; b - bubble grade for movement

TABLE 4 (continued)

DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
27. JH	36/50	SD	S	0	-	0	-	0	-	
28. JH	45/40	IW	S	0	-	0	-	0	-	
29. BH	36/50	IW	S	0	-	0	-	0	-	
30. BH	45/40	SD	S	0	-	0	-	0	-	
31. SMD	27/60	IW	WW	0	-	0	-	0	-	
32. SMD	27/60	SD	WW	0	-	0	-	0	-	
33. SMD	36/50	SD	WW	0	-	0	-	0	-	
34. SMD	36/50	SD	DR	0	-	0	-	0	-	
35. SMD	45/40	IW	DR	0	-	0	-	0	-	
36. SMD	45/40	IW	WW	2/3+	112	2/1+	190	3/3	89	
37. SMD	45/40	SD	WW	0/3+	114	0	-	0	-	Yes
38. SMD	45/40	SD	DR	C	-	0	-	0	-	
39. BM	27/60	SD	DR	0	-	0	-	0	-	
40. BM	36/50	SD	WW	0	-	0/1	135	1/1	114	
41. BM	54/30	SD	WW	0	-	2/1	125	1/1	125	
42. BM	54/30	SD	DR	0	-	0/1	116	1/0	144	
43. MN	27/60	SD	S	0	-	0	-	0	-	
44. MN	36/50	IW	S	0	-	0/1	104	0	-	
45. MN	36/50	SD	S	0	-	1/1	141	2/3	93	
46. MN	54/30	IW	S	0	-	2/2	146	2/2	181	
47. MN	54/30	SD	S	0	-	0	-	0	-	
48. DN	27/60	SD	WW	0	-	0	-	0	-	
49. DN	27/60	SD	DR	0	-	0	-	2/1	138	
50. DN	30/60	IW	WW	0	-	0	-	3-/3	154	
51. DN	30/60	SD	DR	0	-	0	-	2/2	112	
52. DN	36/50	IW	WW	0	-	0	-	1/2	171	
53. DN	36/50	IW	DR	0	-	0	-	2/2	70	Yes
54. DN	54/30	IW	DR	0	-	0/1	200	2/3-	232	
55. GP	27/60	IW	S	0	-	0	-	0	-	
56. GP	27/60	IW	S	0	-	0	-	0	-	
57. GP	30/60	IW	S	0	-	0	-	0	-	
58. AR	27/60	SD	WW	0	-	0	-	0	-	
59. AR	36/50	SD	DR	0/1	92	0	-	0	-	
60. AR	54/30	IW	WW	3+/4	105	1/1	163	2/1	163	
61. AR	54/30	SD	DR	0/1	110	0	-	0	-	
62. AR	54/30	SD	WW	2/3	152	0	-	0/1	98	
63. KR	54/30	SD	S	0	-	1/1	108	0/1	108	
64. RW	30/60	SD	S	0	-	0	-	0	-	

TABLE 5

MAXIMUM BUBBLE GRADES FROM THE PRECORDIAL AND SUBCLAVIAN SITES BY SUBJECT, PROFILE, AND DECOMPRESSION METHOD

	DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
1.	RSD	27/60	IW	DR	0	-	0	-	0	-	
2.	SGG	27/60	IW	DR	0	-	0/1	94	0	-	
3.	SGG	27/60	IW	WW	0	-	0/2	116	0	-	
4.	SMD	27/60	IW	WW	0	-	0	-	0	-	
5.	GP	27/60	IW	S	0	-	0	-	0	-	
6.	GP	27/60	IW	S	0	-	0	-	0	-	
7.	ALH	30/60	IW	DR	0	-	0	-	2/2	86	
8.	DN	30/60	IW	WW	0	-	0	-	3-/3	154	
9.	GP	30/60	IW	S	0	-	0	-	0	-	
10.	ALH	36/50	IW	DR	0/1	60	0	-	0	-	
11.	ALH	36/50	IW	WW	0	-	3/3+	99	1/1	224	
12.	DN	36/50	IW	WW	0	-	0	-	1/2	171	
13.	DN	36/50	IW	DR	0	-	0	-	2/2	70	Yes
14.	BH	36/50	IW	S	0	-	0	-	0	-	
15.	MN	36/50	IW	S	0	-	0/1	104	0	-	
16.	SGG	45/40	IW	WW	0	-	0	-	1/1	131	Yes
17.	SGG	45/40	IW	DR	0	-	0	-	0	-	
18.	SMD	45/40	IW	DR	0	-	0	-	0	-	
19.	SMD	45/40	IW	WW	2/3+	112	2/1+	190	3/3	89	
20.	DE	45/40	IW	S	0	-	0	-	0	-	
21.	JH	45/40	IW	S	0	-	0	-	0	-	
22.	DN	54/30	IW	DR	0	-	0/1	200	2/3-	232	
23.	LBC	54/30	IW	DR	0	-	0	-	0	-	
24.	ALH	54/30	IW	DR	2/3	225	1/1	277	2/1+	179	
25.	ALH	54/30	IW	WW	3/3	117	2/1	174	3+/3+	140	
26.	AR	54/30	IW	WW	3+/4	105	1/1	163	2/1	163	
27.	DE	54/30	IW	S	3/3	170	1/1	218	2/3	195	
28.	MN	54/30	IW	S	0	-	2/2	146	2/2	181	

Explanation of Symbols

Method: SD - surface decompression with oxygen
IW - in-water decompression with oxygen

Role: WW - wet working diver DR - dry resting subject
S - standby diver L - team leader, dry

Code: P - precordial LS - left shoulder RS - right shoulder
a/b: a - bubble grade for rest; b - bubble grade for movement

TABLE 5 (continued)

	DIVER	DIVE (msw/min)	METHOD	ROLE	P	T (min)	LS	T (min)	RS	T (min)	DCS
29.	SGG	27/60	SD	DR	0	-	0	-	0	-	
30.	ALH	27/60	SD	DR	0/2	67	0/1	45	3/4	104	
31.	ALH	27/60	SD	WW	0/1	91	0	-	1/1	116	
32.	SMD	27/60	SD	WW	0	-	0	-	0	-	
33.	AR	27/60	SD	WW	0	-	0	-	0	-	
34.	DN	27/60	SD	WW	0	-	0	-	0	-	
35.	DN	27/60	SD	DR	0	-	0	-	2/1	138	
36.	BM	27/60	SD	DR	0	-	0	-	0	-	
37.	LBC	27/60	SD	S	0	-	0	-	1/1	79	
38.	JDJ	27/60	SD	S	0	-	0	-	0	-	
39.	DE	27/60	SD	S	0	-	0	-	0	-	
40.	MN	27/60	SD	S	0	-	0	-	0	-	
41.	ALH	30/60	SD	WW	0	-	0	-	1/1	55	
42.	DN	30/60	SD	DR	0	-	0	-	2/2	112	
43.	RW	30/60	SD	S	0	-	0	-	0	-	
44.	SGG	36/50	SD	WW	0	-	0	-	0	-	
45.	SGG	36/50	SD	DR	0	-	0	-	0	-	
46.	SMD	36/50	SD	WW	0	-	0	-	0	-	
47.	SMD	36/50	SD	DR	0	-	0	-	0	-	
48.	BM	36/50	SD	WW	0	-	0/1	135	1/1	114	
49.	AR	36/50	SD	DR	0/1	92	0	-	0	-	
50.	JH	36/50	SD	S	0	-	0	-	0	-	
51.	MN	36/50	SD	S	0	-	1/1	141	2/3	93	
52.	DE	36/50	SD	S	0	-	0	-	0	-	
53.	SGG	45/40	SD	DR	0	-	0	-	1+/2	142	
54.	SGG	45/40	SD	WW	0	-	0	-	0	-	
55.	SMD	45/40	SD	WW	0/3+	114	0	-	0	-	Yes
56.	SMD	45/40	SD	DR	0	-	0	-	0	-	
57.	JDJ	45/40	SD	S	0	-	0	-	0	-	
58.	BH	45/40	SD	S	0	-	0	-	0	-	
59.	BM	54/30	SD	WW	0	-	2/1	125	1/1	125	
60.	BM	54/30	SD	DR	0	-	0/1	116	1/0	144	
61.	AR	54/30	SD	DR	0/1	110	0	-	0	-	
62.	AR	54/30	SD	WW	2/3	152	0	-	0/1	98	
63.	MN	54/30	SD	S	0	-	0	-	0	-	
64.	KR	54/30	SD	S	0	-	1/1	108	0/1	108	

TABLE 6

MAXIMUM BUBBLE GRADES OBSERVED IN THE PRECORDIAL REGION AT REST AND FOLLOWING MOVEMENT FOR ALL DIVES

A. In-Water Oxygen Decompression

DEPTH (msw)	BOTTOM TIME (min)	NO. OF SUBJ.	NO. MAN DIVES	MAN-DIVES WITH MAXIMUM BUBBLE GRADE										NO.OF DCS
				AT REST					AFTER MOVEMENT					
				0	1	2	3	4	0	1	2	3	4	
27	60	4	6	6	0	0	0	0	6	0	0	0	0	0
30	60	3	3	3	0	0	0	0	3	0	0	0	0	0
36	50	4	6	6	0	0	0	0	5	1	0	0	0	1
45	40	4	6	5	0	1	0	0	5	0	0	1	0	1
54	30	6	7	3	0	1	3	0	3	0	0	3	1	0
TOTALS			28	23	0	2	3	0	22	1	0	4	1	2

B. Surface Decompression with Oxygen

DEPTH (msw)	BOTTOM TIME (min)	NO. OF SUBJ.	NO. MAN DIVES	MAN-DIVES WITH MAXIMUM BUBBLE GRADE										NO.OF DCS
				AT REST					AFTER MOVEMENT					
				0	1	2	3	4	0	1	2	3	4	
27	60	10	12	12	0	0	0	0	10	1	1	0	0	0
30	60	3	3	3	0	0	0	0	3	0	0	0	0	0
36	50	7	9	9	0	0	0	0	8	1	0	0	0	0
45	40	4	6	6	0	0	0	0	5	0	0	1	0	1
54	30	4	6	5	0	1	0	0	4	1	0	1	0	0
TOTALS			36	35	0	1	0	0	30	3	1	2	0	1

TABLE 7

MAXIMUM BUBBLE GRADES OBSERVED IN THE SUBCLAVIAN VEINS AT REST AND FOLLOWING MOVEMENT FOR ALL DIVES

A. In-Water Oxygen Decompression

DEPTH (msw)	BOTTOM TIME (min)	NO. OF SUBJ.	NO. MAN DIVES	MAN-DIVES WITH MAXIMUM BUBBLE GRADE										NO. OF DCS
				AT REST					AFTER MOVEMENT					
				0	1	2	3	4	0	1	2	3	4	
27	60	4	6	6	0	0	0	0	4	1	1	0	0	0
30	60	3	3	1	0	1	1	0	1	0	1	1	0	0
36	50	4	6	3	1	1	1	0	2	1	2	1	0	1
45	40	4	6	4	1	0	1	0	4	1	0	1	0	1
54	30	6	7	1	0	5	1	0	1	2	1	3	0	0
TOTALS			28	15	2	7	4	0	12	5	5	6	0	2

B. Surface Decompression with Oxygen

DEPTH (msw)	BOTTOM TIME (min)	NO. OF SUBJ.	NO. MAN DIVES	MAN-DIVES WITH MAXIMUM BUBBLE GRADE										NO. OF DCS
				AT REST					AFTER MOVEMENT					
				0	1	2	3	4	0	1	2	3	4	
27	60	10	12	8	2	1	1	0	8	3	0	0	1	0
30	60	3	3	1	1	1	0	0	1	1	1	0	0	0
36	50	7	9	7	1	1	0	0	7	1	0	1	0	0
45	40	4	6	5	1	0	0	0	5	0	1	0	0	1
54	30	4	6	3	3	0	0	0	2	4	0	0	0	0
TOTALS			36	24	8	3	1	0	23	9	2	1	1	1

TABLE 8

COMPARATIVE PROFILES FOR K-S 1971 STANDARD AIR DIVES

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)						Decom. Time (min)
		18	15	12	9	6	3	
27	60	-	-	-	4	10	21	35
30	60	-	-	-	8	11	29	48
36	50	-	-	5	8	13	34	60
45	40	-	5	6	9	13	42	75
54	30	3	5	6	9	13	40	76

Note: Decompression times calculated for 200 metres altitude

LIST OF FIGURES

Figure 1. Comparison of total decompression times for 27 msw from the KS-1971 decompression computer model, Royal Navy Table 11 Air Table, and the U.S. Navy Standard Air Tables (90 fsw).

Figure 2. Comparison of total decompression times for 45 msw from the KS-1971 decompression computer model, Royal Navy Table 11 Air Table, and the U.S. Navy Standard Air Tables (150 fsw).

Figure 3. Dive profiles for 45 msw for 40 min for standard air decompression, in-water O_2 decompression, and surface decompression with O_2. For in-water O_2 decompression, O_2 starts when 9 msw is reached and continues to the end of the dive. For surface decompression, O_2 starts at 9 msw in-water and continues to the end of the dive except for the 4 min period while the divers are on the surface.

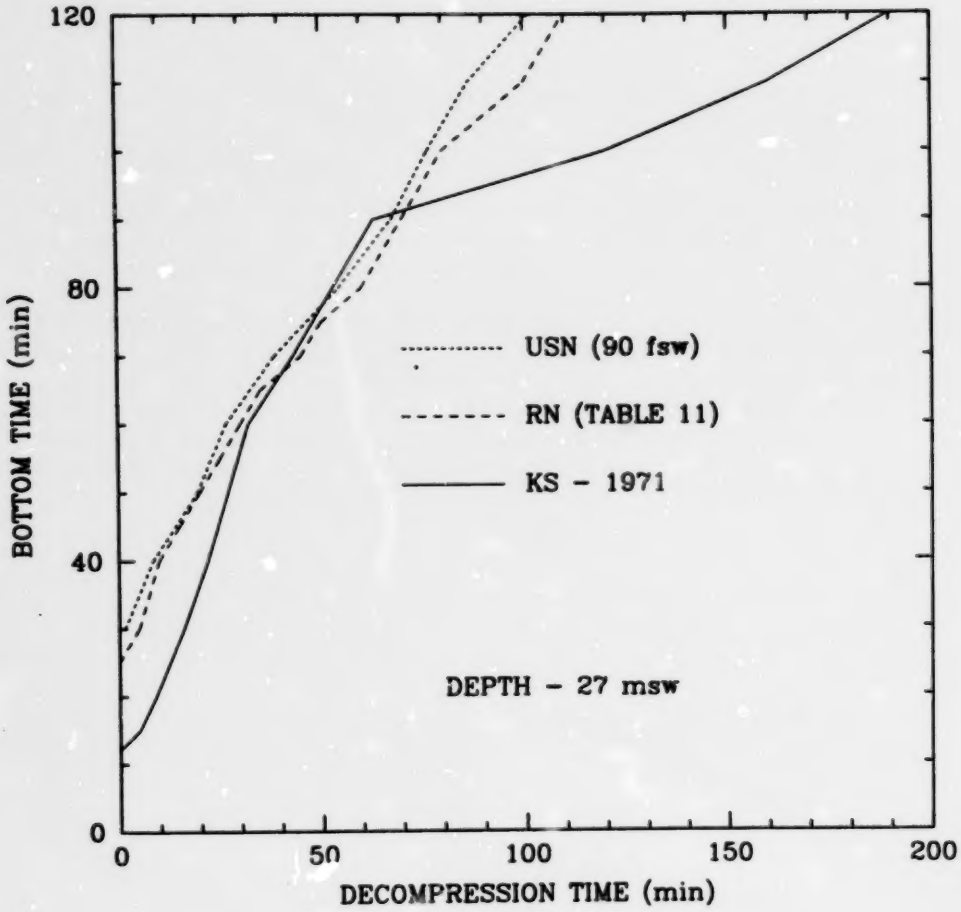

Figure 1. Comparison of total decompression times for 27 msw from the KS-1971 decompression computer model, Royal Navy Table 11 Air Table, and the U.S. Navy Standard Air Tables (90 fsw).

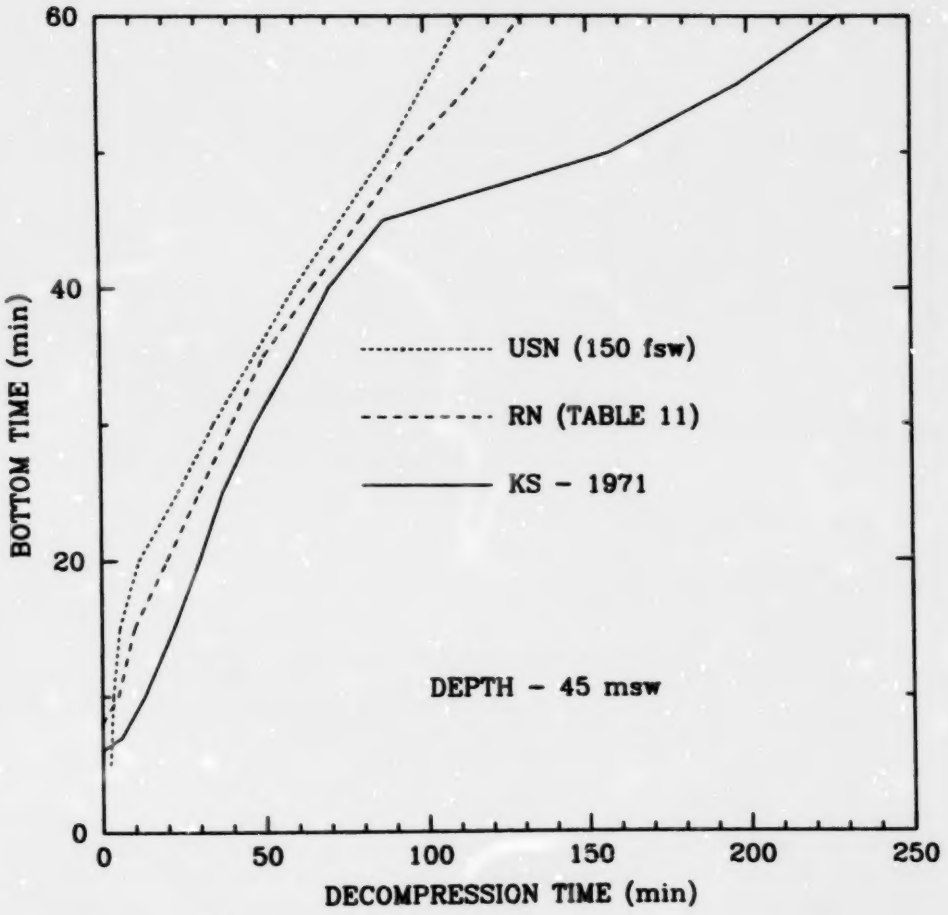

Figure 2. Comparison of total decompression times for 45 msw from the KS-1971 decompression computer model, Royal Navy Table 11 Air Table, and the U.S. Navy Standard Air Tables (150 fsw).

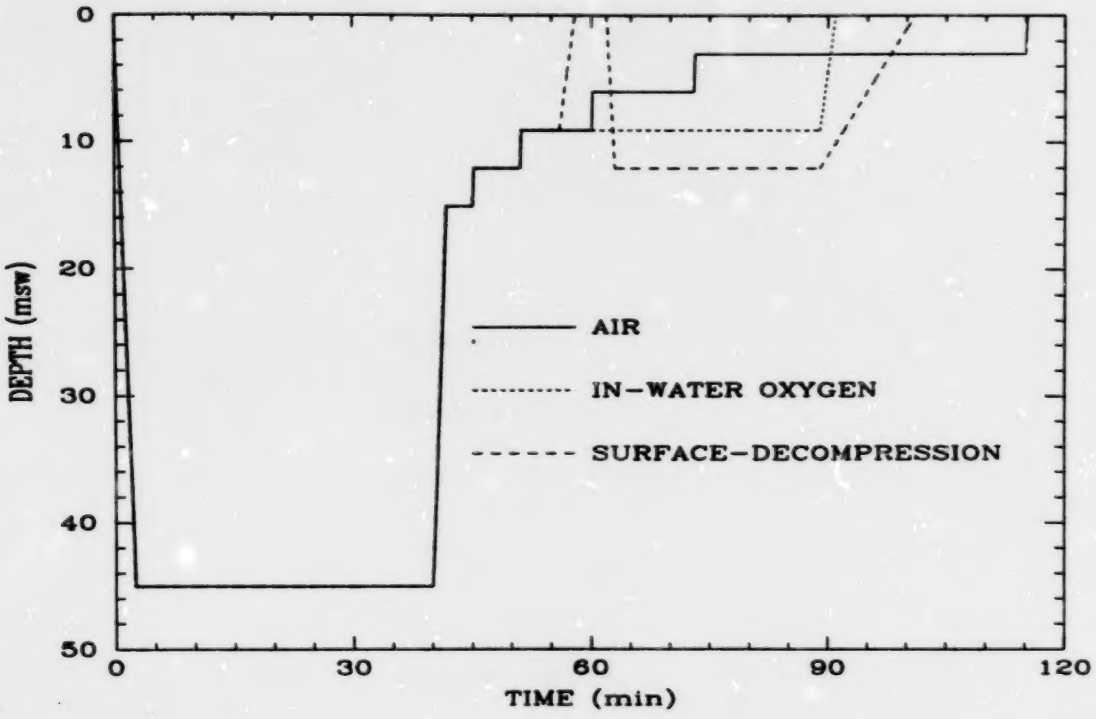

Figure 3. Dive profiles for 45 msw for 40 min for standard air decompression, in-water O_2 decompression, and surface decompression with O_2. For in-water O_2 decompression, O_2 starts when 9 msw is reached and continues to the end of the dive. For surface decompression, O_2 starts at 9 msw in-water and continues to the end of the dive except for the 4 min period while the divers are on the surface.

APPENDIX

CALCULATION OF OXYGEN DECOMPRESSION PROCEDURES FOR THE XDC-2 DECOMPRESSION COMPUTER

The Kidd-Stubbs (KS) 1971 model, on which the XDC-2 is based, is defined by a set of four non-linear differential equations:

$$dP_i/dt = A[(B + P_{i-1} + P_i)(P_{i-1} - P_i) - (B + P_i + P_{i+1})(P_i - P_{i+1})]$$

where: P_i = the pressure in compartment i, i = 1-4,
P_0 = the ambient pressure,
$P_5 = P_4$ (no fifth compartment), and
A, B are constants which determine the uptake and elimination rates of the gas into the model.

All calculations are normally made for total gas pressure, so that the ambient pressure, P_0, is always entered as the absolute value of the hydrostatic pressure. Ideally, P_0 should be zero for O_2 decompression since there should be no inert gas being breathed. In practice, however, O_2 decompression may not be 100% efficient since there may be some leakage of the ambient gas around the face mask. For calculating the compartment pressures when O_2 is used, a 20% leakage of ambient gas into the face mask has been assumed. For example, if O_2 is being breathed at 9 metres of seawater (msw), P_0 is assumed to be 3.8 msw (absolute).

The KS-1971 model with O_2 can be used to generate surface decompression tables. However, the surface interval "violates" the computed safe ascent depth and, theoretically, invalidates all subsequent computations of the safe depth. To determine whether these calculations are valid, it is necessary to compare the decompression times with those of tables known to be relatively safe. The surface decompression tables chosen for comparison were those developed by Arntzen and Eidsvik [Reference 13] at the Norwegian Underwater Institute (NUI). These NUI tables were a modification, based on commercial diving experience in the North Sea, of the US Navy "Surface Decompression Table using Oxygen" [Reference 8]. They were calculated from the USN tables by applying a bottom time correction which increased linearly with depth from 20 msw. The resulting decompression times are thus more conservative than the USN decompression times.

To allow a valid comparison, the conditions used in generating surface decompression tables from the KS model were the same as those specified by Arntzen and Eidsvik. These were:

Descent rate	18 msw/min
Initial ascent rate	7.5 msw/min
Final in-water decompression stop	9 msw on air
Ascent to surface from 9 msw	1 min
Time on surface	3 min

Recompress to 12 msw on O_2	1	min
O_2 decompression at 12 msw		
Air breaks every 20 min		
Ascent rate from 12 msw to surface	1	msw/min

The results are shown in Table A together with the decompression times from the NUI tables for comparison.

For depths less than 45 msw, the KS decompression times are similar to those of the NUI tables. For the shorter bottom times, the O_2 stop times are almost identical. As the bottom time increases, the O_2 stop time becomes less for the KS model, but this is offset by a longer in-water decompression time at 9 msw or deeper, thus keeping the total decompression time approximately the same as those for the NUI tables.

For depths greater than 45 msw, the total decompression times are still similar for shorter bottom times. However, for longer bottom times, the NUI decompression times become longer, for both the in-water decompression stops and the 12 msw chamber stop. This is a result of the nature of the correction applied by Arntzen and Eidsvik, which corrects the short and shallow dives the least and the long and deep dives the most. Whether such large corrections are necessary is uncertain. The deepest depth used for comparison is 51 msw since the NUI tables do not extend beyond this depth.

Thus, this comparison appears to show that the KS model can generate safe decompression tables, at least, with the same safety as the NUI tables. Whether the decompression times for the longer and deeper dives are adequate will have to determined by testing. At least, the KS decompression times for this range have been generated from a consistent model which appears to give adequate decompression for depths less than 45 msw.

For the actual surface decompression tables to be tested with the XDC-2 decompression computer, the dive conditions were changed from those used by Arntzen and Eidsvik. The changes were:

Initial ascent rate	18 msw/min
Final in-water decompression stop	9 msw on O_2
Ascent to surface from 9 msw	2 min on O_2
Time on surface	4 min
No air breaks at 12 msw	

All other conditions remained the same. The surface interval allowed from the time of leaving the in-water stop at 9 msw to the time 12 msw is reached in the RCC was 7 min. The 2 min ascent from 9 msw was dictated by the vent rate of the DRF.

TABLE A
COMPARISON OF SURFACE DECOMPRESSION TIMES DERIVED FROM THE KIDD-STUBBS MODEL WITH NORWEGIAN UNDERWATER INSTITUTE TIMES

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)									Decom. Time (min)
		In-Water Stops				Surface			Chamber		
		Air				Air		O_2	O_2		
		18	15	12	9	Asc	SI	Des	12	Asc	
27	60	-	-	-	4	1	3	1	16	12	37X
		-	-	-	3	1	3	1	18	12	38N
	90	-	-	-	8	1	3	1	29	12	59X
		-	-	-	3	1	3	1	33	12	58N
30	40	-	-	-	4	1	3	1	10	12	31X
		-	-	-	3	1	3	1	10	12	30N
	60	-	-	-	8	1	3	1	20*	12	50X
		-	-	-	3	1	3	1	24*	12	49N
	80	-	-	-	11	1	3	1	31*	12	64X
		-	-	-	3	1	3	1	37*	12	62N
36	30	-	-	-	6	1	3	1	10	12	33X
		-	-	-	4	1	3	1	12	12	33N
	50	-	-	5	8	1	3	1	22*	12	57X
		-	-	-	6	1	3	1	30*	12	58N
45	25	-	-	5	7	1	3	1	12	12	41X
		-	-	-	7	1	3	1	19	12	43N
	40	-	5	6	9	1	3	1	28*	12	70X
		-	6	6	9	1	3	1	36*	12	79N
51	15	-	-	-	9	1	3	1	9	12	35X
		-	-	-	6	1	3	1	11	12	34N
	30	-	7	6	8	1	3	1	24*	12	67X
		9	5	9	6	1	3	1	34*	12	85N

X - Kidd-Stubbs calculation; N - NUI modified tables
* Add 5 min air break after 20 min on O_2